UCRL-TR-215651

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Probing the Universe with Mirrors That Trick Light

A. Hazi

September 26, 2005

Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

November 2004

Science & Technology REVIEW

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Probing the Universe

Reprinted from Science & Technology Review, November 2004

UCRL-TR-215651

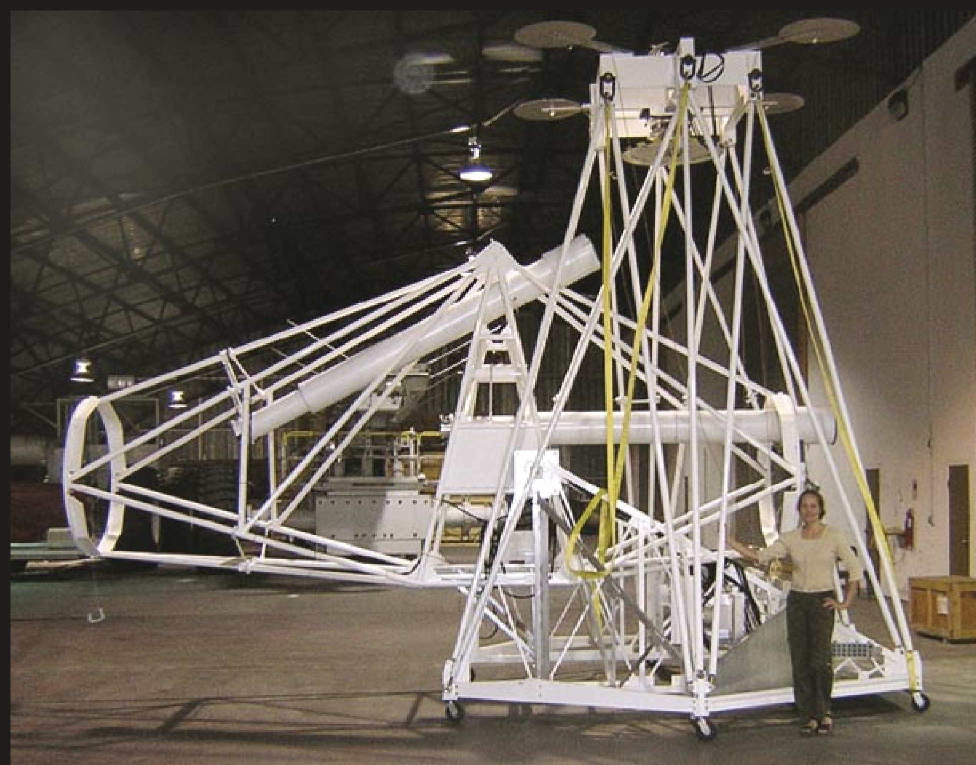
Probing the Universe with Mirrors That Trick Light

FOR astrophysicists, stargazing may be different than for most people, who are content to admire a star's beauty or possibly make a wish. More than a few astrophysicists wish they could be closer to the stars—or to at least have more sophisticated probing instruments—to understand more about the universe. Astrophysicists study x rays originating from our Sun, stars, and supernova remnants to understand the extreme physical processes occurring there.

In recent years, Livermore researchers have developed optics for astrophysical applications that can focus hard x rays (that is, x rays with energy levels above 20 kiloelectronvolts) emanating from celestial objects, such as supernovae. In addition to astrophysics, hard x-ray optics have a variety of possible applications, including medical imaging, laser target characterization, and radiation detection.

Livermore researchers have long contributed to advancements in supernova astrophysics because studying thermonuclear processes is a central part of the Laboratory's national security mission, and the physical processes involved in a nuclear weapon and an exploding star are similar.

Livermore physicist Bill Craig, who is involved in several projects using x-ray optics, says, "We can do a better job of detecting illicit radioactive sources because of what we have learned from our developments in astrophysics. Whether the radiation source is from a black hole in space or nuclear material in a dirty bomb, detecting the source involves the same challenge, which is to pick up faint signals (high-energy photons) amidst background radiation."



The High Energy Focusing Telescope uses three high-energy x-ray focusing optics modules and cadmium–zinc–telluride detectors to observe some of the most energetic objects in space.

Up, Up and Away

Recently, Livermore partnered with the California Institute of Technology (Caltech), Columbia University, and the Danish Space Research Institute (DSRI) to build the High Energy Focusing Telescope (HEFT), which was awaiting a balloon-launch into Earth's atmosphere at press time. The telescope uses optics that provide a dramatic improvement in sensitivity and angular resolution over previous instruments and allow scientists to observe hard x rays emitted by some of the most energetic objects known, including supermassive black holes, stars, and pulsars. (See the box on p. 6.) Livermore researchers are most interested in measuring x and gamma rays of titanium-44, a radioactive isotope of titanium produced in supernovae.

The Electromagnetic Universe

The entire range of light energies, including what humans can and cannot see, is called the electromagnetic spectrum. The range includes (from lowest to highest energy level) radio waves, microwaves, infrared, optical, ultraviolet, x rays, and gamma rays. Researchers describe the types of electromagnetic radiation by energy, wavelength, or frequency. The name distinctions are due to the vast differences in energy between the types and provide researchers with a practical way to reference them.

Light acts like both a particle and a wave and comes in discrete amounts—the least being a simple photon. Low-energy photons, for example radio waves, tend to behave more like waves, while higher energy photons, such as x rays, behave more like particles. These differences affect how researchers build instruments to measure photons. Celestial gamma and x rays are most accurately measured above Earth's atmosphere because they are absorbed as they travel through the atmosphere.

When scientists observe the sky at low x-ray energies (0.25 kiloelectronvolt), they see a glow from the radiation emitted from hot gas that fills some of the space between the stars. Because of the galaxy's shape, radiation from within it is brighter in some directions and dimmer in others. When scientists observe the sky at higher x-ray energies (above 0.50 kiloelectronvolt), the background radiation appears isotropic; that is, it looks the same in all directions. As a result, scientists believe that higher-energy x rays come from outside the galaxy.

A variety of celestial objects also emit x rays, including single stars, binary star systems, supernova remnants, galaxies, clusters of galaxies, and active centers of galaxies (active galactic nuclei, or AGN). X rays usually come from very hot gaseous matter (millions of kelvins) or from very fast electrons losing their kinetic energy. AGNs emit both x and gamma rays. Because AGNs can undergo changes in much less than 1 second, researchers study them at all wavelengths. X rays emitted from AGNs can provide scientists with insights into the physical processes occurring there.

Researchers are interested in titanium-44 because it is formed at the mass cut, the boundary between material that is ejected from a supernova and the material that is captured by gravity and forms a neutron star. The mass-cut region provides the deepest possible view into the details of the supernova explosion. Craig says, "Because we know titanium-44 has a half-life of approximately 80 years, we can look at the distribution of titanium-44 and learn more about what happened at the time a star exploded." All of the calcium in our bodies also comes from the decay of titanium-44 in supernovae, an interesting irony considering titanium is often a surgeon's material of choice when replacing damaged bones. HEFT will focus on Cassiopeia A, a supernova remnant that appears to be 327 years old. (The distance to Cassiopeia A from Earth is approximately 10,000 light years, so the star's explosion actually occurred more than 10,300 years ago.)

With funding from Livermore's Laboratory Directed Research and Development Program, Livermore also developed the technology that was used for building the gondola to hold HEFT's optics. "Building the gondola was a challenge because we had a 1,400-kilogram instrument suspended from a balloon as big as a football stadium," says Craig. "The gondola has to hold this instrument steady at an altitude of 40 kilometers to lock the telescopes onto a source with a precision equal to three times the width of a human hair." The HEFT team also built star trackers that can lock onto stars during the day or night to accurately ascertain the position of the gondola and point the optics toward an x-ray source.

X rays are photons with energy levels that range from approximately 0.1 to 100 kiloelectronvolts. (For comparison, visible light has an energy level of 0.002 to 0.003 kiloelectronvolt.) Energies in the lower end of the range are called soft x rays, and those in the higher end are called hard x rays. Measuring x rays from the Earth's surface is impossible, because they are mostly absorbed by Earth's atmosphere. Instead, detectors must be deployed at an altitude that places them above 99 percent of the atmosphere.

In 1995, Livermore helped launch the Gamma Ray Arcminute Telescope Imaging System (GRATIS), which was one of the first high-altitude balloons to carry a high-energy imager. The optics system consisted of 36 coded-aperture-based telescopes. In a coded-aperture-based telescope, an image of the source is encoded on a detector by placing a sheet pierced with a hole pattern in front of the detector. The holes in the mask project a pattern on the detector so that the direction of the incoming photons can be inferred. The GRATIS balloon reached an altitude of 40 kilometers and remained aloft for 36 hours. GRATIS tracked a number of astronomical gamma and x-ray sources, including the center of our galaxy, a prime black hole candidate (Cyg X-1), and an unusual x-ray binary system (Cyg X-3).

Craig notes that both coded-aperture-based systems, such as the one used for GRATIS, and focusing optics-based systems are valuable, depending on the application. "If we want to view the whole sky at once, a coded-aperture-based system is best. But if we need to focus on one specific area and learn as much as we can about it, focusing optics are much better, increasing sensitivity by as much as a factor of 1,000 over coded-aperture-based systems."

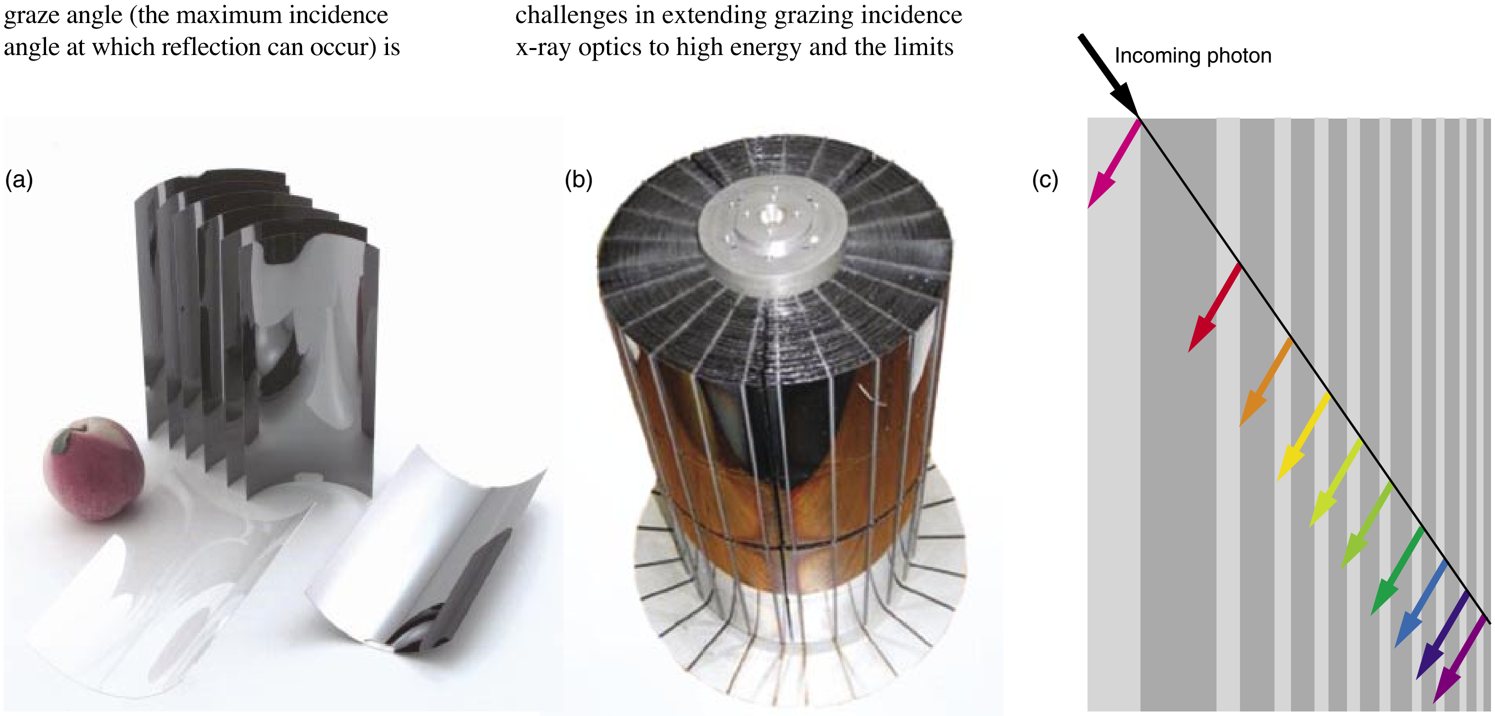
In addition to the interference from Earth's atmosphere, another challenge when measuring x rays is they don't reflect off an optic's glass surface in the same way that visible light does in traditional telescopes. Because of their high energy, most x-ray photons will penetrate the mirrors and be absorbed if they approach at a perpendicular angle. At this angle, no photons would be reflected onto the detectors that measure their position and energy. Researchers found that for high-energy focusing optics, they must design mirrors nearly parallel to incoming x rays to maximize the reflected light. In this configuration, the photons glance off the surface of the mirrors, in much the same way a stone is thrown to skip over water. The critical graze angle (the maximum incidence angle at which reflection can occur) is inversely proportional to the photon energy, so reflecting high-energy x rays requires very small incidence angles. For example, the critical angles for x rays emitted from iridium at energy levels of 1, 10, and 100 kiloelectronvolts are approximately 2.0, 0.6, and 0.1 degrees, respectively.

Focusing X Rays Where They Count

In 1952, German physicist Hans Wolter designed a nearly cylindrical mirror that increases collection efficiency and brings x rays to a common focus. Technology at the time prevented Wolter from accomplishing his goal to construct a short-wavelength microscope for biological research. However, his design advanced the development of focusing optics for telescopes.

When focusing telescopes were first developed, they were limited to the soft x-ray band because of the technical challenges in extending grazing incidence x-ray optics to high energy and the limits in spatial resolution that existing hard x-ray detectors could achieve. Recent developments in multilayer optics and high-atomic-number (high-*Z*) solid-state pixel detectors now make both focusing optics and detectors possible at high x-ray energies. These advances provide improvements in sensitivity and resolution far beyond what are achievable with coded-aperture-based instruments.

HEFT collaborators found they could increase the optics' efficiency by collecting light from a larger aperture using a multilayer structure invented specifically for hard x-ray optics. A multilayer is a coating composed of alternating layers of high- and low-atomic-number materials, such as molybdenum and silicon or tungsten and boron carbide. The varying thickness of the layers within the coating makes the



(a) The High Energy Focusing Telescope's (HEFT's) optic mirrors are made from glass originally developed for flat-panel computer monitors. The glass is thermally formed and then covered with a multilayer coating composed of alternating layers of materials that vary in thickness. (b) Seventy-two mirror shells are assembled for each of HEFT's three telescopes. (c) The multilayer structure is efficient for a wide range of angles and photon wavelengths (energies). Photons are reflected off the interface between the different materials, thus "tricking" light into seeing more mirrors. The colored arrows indicate the reflectivity from a range of x-ray energies, from the lowest (pink arrow) to the highest (violet arrow).

design efficient for a wide range of angles and photon wavelengths (energies). "In a straightforward approach, we would have to add more glass—thousands of mirrors—to get the reflectivity to cover the emitting source area we need to measure," says Craig. "Instead, we looked at how we could change the critical graze angle. The multilayer approach works because it 'tricks' light into seeing a number of mirrors."

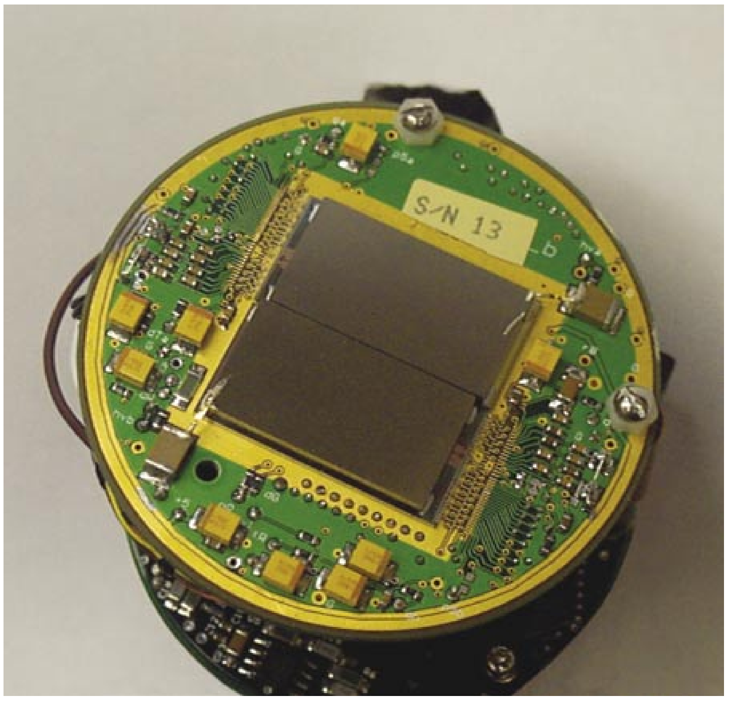
Each telescope on HEFT features Caltech's innovative detector system, which has two solid-state, cadmium–zinc–telluride pixel detectors, each with more than 1,000 pixels. A high-*Z* element, such as cadmium, increases a detector's sensitivity and spatial resolution because the large number of protons and neutrons in its nucleus makes it more efficient at stopping photons. In addition, each detector is bonded to a custom silicon chip that contains an amplifier with microelectronics for every pixel. Each 500- by 500-micrometer pixel can thus measure photon energy and spatial resolution.

Craig says, "In traditional systems, an external amplifier is connected to a detector. With those systems, we can measure the energy, but we can't be certain of its directional source because we don't know where on the detector the photon hit. And, if we subdivide the detector and increase the number of amplifiers to improve spatial resolution, we end up with a very large system that becomes impractical." The focusing optics system also dramatically limits background emissions from the atmosphere and high-energy cosmic-ray particles from interfering with the detector.

Low-Cost Fabrication Techniques

Producing high-quality reflective optics can be expensive. For example, the National Aeronautics and Space Administration (NASA) spent $700 million to make the four sets of mirrors for the Chandra X-Ray Observatory launched in 1999. The costly processing technique involved carving ceramic glass from a monolithic blank, and then polishing and measuring each mirror. Once the substrate was finished, a reflective coating was deposited on the interior of the optic. HEFT required 72 mirror shells on each of its three telescopes, so the cost to produce the mirrors using this method would have been prohibitive.

The HEFT team developed a new fabrication method that was comparatively inexpensive at $100,000 per telescope. The process starts with a thin glass originally developed as a substrate for flat-panel displays on computer laptops. The inexpensive and high-quality glass is inherently smooth and eliminates the need for polishing, which is one of the most labor-intensive steps in other techniques. The flat sheets are thermally formed into the appropriate shape and then covered with a thin multilayer. Small pieces of graphite are inserted between the mirrors to precisely position each mirror and provide space for the photons to reflect off the mirrors. Columbia University prepared the glass for HEFT, and a Livermore engineering team, led by Todd Decker, developed the assembly method.



Each of the High Energy Focusing Telescope's three optic modules focuses x rays onto a solid-state detector. The detector consists of two pieces of cadmium–zinc–telluride, each of which is 2.6 by 1.3 centimeters wide and 2 millimeters thick. The large number of protons and neutrons in cadmium's nucleus make the material efficient at stopping photons.

Rising Above the Atmosphere

Telescopes launched into the atmosphere by balloon are relatively inexpensive compared with telescopes launched into space by satellites. However, the balloons can rise only 40 kilometers above Earth, and atmosphere above this height can interfere with measurements. In addition, the lifetime of helium-filled balloons is limited; they can float at the required altitude for only a day or two.

NASA is studying a proposal by the HEFT team to build the Nuclear Spectroscopic Telescope Array (NuSTAR), which will take a telescope for focusing high-energy x rays into space and above the atmospheric interference. NuSTAR will fly 525 kilometers above Earth's surface and stay in orbit for 3 years. It will be the first hard x-ray focusing telescope in space and will observe energies from 10 to about

100 kiloelectronvolts, providing a 1,000-fold increase in sensitivity over previous missions.

NuSTAR will survey galactic nuclei, observe the synthesis of elements in supernova remnants, and study high-energy blazers. NuSTAR's focusing optics will function similarly as they did for HEFT, but NuSTAR will have 130 nested mirror shells on each of its 3 telescopes. The HEFT team, in partnership with NASA's Jet Propulsion Laboratory, proposed building NuSTAR, and their proposal was selected in mid-2003 as one of five missions now engaged in a year-long competition for two flight opportunities as part of NASA's Small Explorer Program. NASA plans to announce the two winning missions, which would launch in 2007 and 2008, in November 2004.

Adapting the Technology

Livermore's collaborative projects sometimes reap bigger dividends than planned when applications spin off in unexpected directions. For example, the same technology Caltech used to build the detector system for HEFT has been adopted for use on RadNet, a Livermore-developed radiation detector for homeland security. (See *S&TR,* September 2004, pp. 4–11.)

In 2001, Craig and Simon Labov, director of Livermore's Radiation Detection Center (RDC), were discussing radiation detection requirements at an RDC workshop when Labov expressed the need for a handheld system that could run on batteries and be capable of high spatial resolution. Fresh from the collaborative effort on HEFT, Craig believed its detector technology could be applied to a handheld radiation detector. Caltech had not yet published data on its detector technology. However, Craig's collaborations on HEFT, and later with the RDC, spawned the needed technology to develop RadNet.

RadNet combines a cellular telephone, a personal digital assistant with Internet access, and a Global Positioning System locator with a radiation sensor. Because the instrument is inexpensive, first responders can take a number of them in the field to cover a wide geographic area. "It's amazing," says Craig, "how much of our work comes full circle. We're now using what we've learned from the detector technology in RadNet to build a larger array for the Energetic X-Ray Imaging Survey Telescope, another large NASA project to study black holes."

The Nuclear Spectroscopic Telescope Array (artist's conception shown here) would be the first satellite mission with a high-energy x-ray focusing telescope in space and would provide a 1,000-fold increase in sensitivity over previous missions.

The $30,000 Mouse

The Laboratory is also applying its x-ray optics expertise to medical imaging. Livermore physicist Michael Pivovaroff leads a team developing x-ray optics for cameras to image mice used in research. The Small Animal Radionuclide Imaging System is funded through the Department of Energy's Office of Biological and Environmental Research and the Campus–Laboratory Collaborations Exchange Program administered by the University of California (UC) Office of the President. The project brings together researchers from Livermore, UC San Francisco and Berkeley, NASA's Marshall Space Flight Center, and DSRI.

Advances in transgenic manipulation (altering the genome of a species by introducing a gene or genes of another species) have allowed researchers to produce genetically engineered mice with human diseases. By creating and analyzing animals that harbor a known condition or planned changes in genes, biomedical researchers can observe how effective a treatment is or how well a drug controls DNA damage or carcinogenesis. Each of these mice can cost as much as $30,000. They hold tremendous promise to help solve human health problems.

Nuclear medicine studies of animals and humans currently rely on single-photon emission tomography or positron emission tomography. These collimator-based imaging techniques are limited to spatial resolutions between 1 and 2 millimeters. However, many research problems can be addressed only with a resolution of about 100 micrometers, which is 10 times finer. Also, because a single cell measures just tens of micrometers across, waiting for a tumor to reach the 1-millimeter size required by conventional imaging techniques prevents researchers from studying the critical first stages of tumor development. With current techniques, it would either be impossible or prohibitively expensive to construct an instrument with greater resolution.

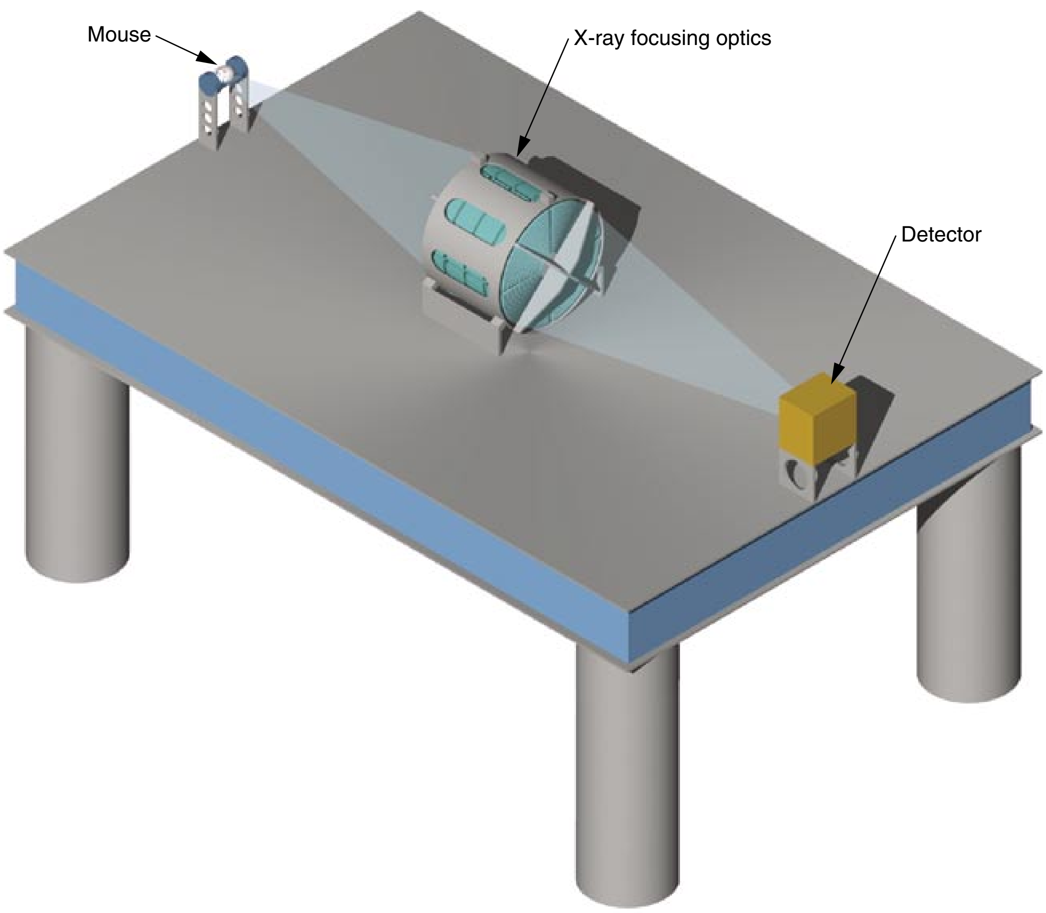
The Livermore team plans to increase the resolution to 100 or possibly 10 micrometers by bending the shape of the multilayer mirrors used for the telescope design and adapting them for use in a microscope. Pivovaroff says, "Limits in optical fabrication and coating techniques prevented Wolter from fulfilling his dream of constructing a short-wavelength microscope for biological research in the 1950s. Today, we have the technology to realize his vision."

This increase in resolution will allow in vivo assessment of biological and biomolecular interactions in mice and other small animals. It will also allow researchers to administer lower doses of radioisotopes, which will lessen the chance for the radioisotope to adversely affect results.

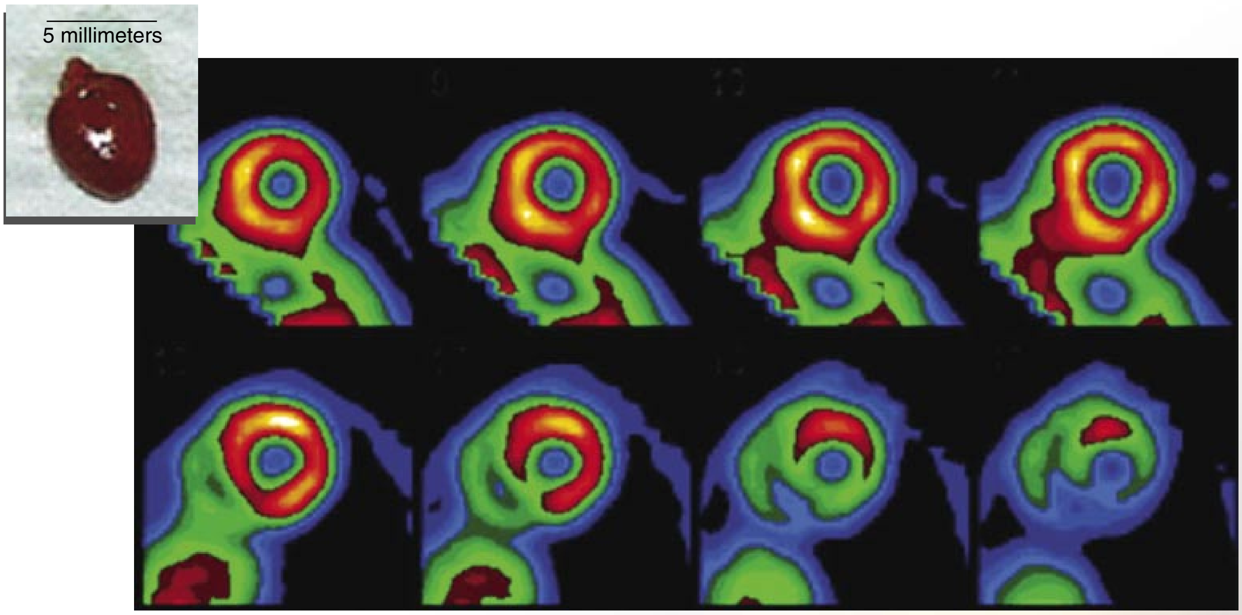
The Livermore team designed several biological optics systems using Monte Carlo simulations of optical designs and multilayer methods. One design for imaging iodine-125 consists of 102 nested mirror shells and can resolve up to 145 micrometers. Recent experiments with single-shell prototypes achieved the expected resolution and demonstrated that practical optics can be built with 10 times better resolution and efficiency than most pinhole collimators.

Verifying Targets

X-ray optics may also prove valuable for target characterization and imaging on experiments at the National Ignition Facility (NIF). Researchers need to be able



X-ray focusing optics are being adapted in a microscope design for the Small Animal Radionuclide Imaging System. In the design shown here, the optics will focus x rays emitted from a mouse that is injected with iodine-125 onto a detector.



This false-color image shows a mouse heart injected with an iodine-125 agent. In the tomographic reconstruction, the brighter colors correspond to more emission from that region of the heart wall. (Image courtesy of the University of California at San Francisco.)

to verify nondestructively that mesoscale (the length scale between macro and nano) parts are assembled correctly. The parts must not be damaged before they become a component of an experiment. (See *S&TR,* October 2003, pp. 18–26.) Many techniques already exist to characterize objects, but they cannot image through high-*Z* materials.

NIF researchers also need to confirm their experimental results. For example, if they suspect that light will be emitted in a certain direction, they need an imaging tool that can measure it. One possible method is to use reflective optics to image x rays emitted during an experiment. Livermore's work on extreme ultraviolet lithography, of which multilayers are an important component, will contribute to improving the resolution of these systems and may, ultimately, lead to the development of diffraction-limited x-ray optics.

Fortunately, the bright stars we gaze upon reveal not only beauty but also a treasure trove of valuable information. The fact that the stars are actually a vision created thousands of years ago only adds to their allure and to the value of the information scientists can gather.

As Livermore continues to explore thermonuclear fusion as part of its national security mission, Laboratory researchers can look upward for more answers from the stars.

—Gabriele Rennie

Key Words: Gamma Ray Arcminute Telescope Imaging System (GRATIS), hard x ray, High Energy Focusing Telescope (HEFT), multilayer-coated mirrors, Nuclear Spectroscopic Telescope Array (NuSTAR), Small Animal Radionuclide Imaging System, x-ray optics.

For further information contact Bill Craig (925) 423-1471 (craig1@llnl.gov).

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.